

Empirical Model of Residual Element Content in Steel when Three-Component Burden is Used in the Process of Steel Production in Electric Arc Furnace

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Abstract- The article describes the technology of steelmaking in electric arc furnaces using three-component burden. It presents the experimental studies results of residual element content in steel. It also gives the findings of chrome, nickel and copper content obtained on the basis of the structural system of interrelated equations.

Keywords- *Steelmaking Technology; Burden Materials; Waste Metal; Scrap; Cast Iron; Residual Elements; Burden Mix*

I. INTRODUCTION

Modern industrial enterprises impose heavy demands on the quality of metallurgical products. Purposeful study of all production stages used in the steelmaking process starting from burden material preparation contributes to meeting these demands. OJSC “Magnitogorsk Iron and Steel Works” (OJSC “MMK”), being one of the biggest metallurgical enterprises of Russia, has two 180 t electric arc furnaces.

In order to develop a control system of steelmaking in electric arc furnaces, it is necessary to determine sets of input parameters influencing the technological modes of the process. According to the design documents of the company VAI-FUCHS and the current technology regulations of steelmaking at OJSC “MMK”, the main parameters controlling power, slag and blowing mode are the geometry of the scrap charged and the burden materials ratio.

II. INFLUENCE THE RESIDUAL ELEMENTS ON FURTHER TECHNOLOGICAL PROCESSES AND FINAL PROPERTIES OF STEELS

Burden materials containing cast iron, waste metal and scrap are used in the electric arc furnaces of OJSC “MMK”. According to the contract with VAI-FUCHS three combinations of waste metal and cast iron can be used as the burden mix: 100% of waste metal; 75% of waste metal and 25% of cast iron; 60% of waste metal and 40% of cast iron. The proposed ratios do not make provisions for application of scrap currently contained in the burden in the EAF. In 2011 a study aimed at determining of the influence of burden materials ratios (waste metal, scrap, cast iron) on residual element content in the steel produced in the EAF was carried out in the electric steelmaking shop of OJSC “MMK”. The results of primary initial data processing are given in Fig. 1.

The mean value of the used burden materials share during the study was the following: 63% of waste metal, 26% of cast iron and 11% of scrap.

The residual elements have significant influence on further technological processes and final properties of steels. The active constraints of the content level of residual elements are set depending on the purpose of the metal products. Copper and its combinations with other elements is one of the most important residual elements. The influence of residual elements can be seen on the properties of finished products, in particular:

- hot brittleness due to high copper content and grain-boundary segregation [2];
- percent elongation [1] and drawability as a result of the matrix strengthening and having a positive influence on strain capacity provided the material undergoes proper machining and thermal treatment;
- hardening characteristics increasing as a result of slower reactions of ferrite and pearlite formation;
- strength and ductility changing as a result of solidification with grain-boundary precipitation [3];
- embrittlement on the grain boundaries caused by elements segregation on the grain boundaries during cooling, coiling and finish annealing.

A lot of chemical elements get into steel with the waste metal charged into the EAF. Great attention is paid to the content of chrome, nickel and copper in burden materials and their content is given in Table I.

At present the target residual element (chrome, nickel and copper) content for steels of different purposes is given in Table II.

TABLE I CONTENT OF CHEMICAL ELEMENTS ENTERING THE BURDEN WITH WASTE METAL

Kind of Waste Metal	[Cr]. %	[Ni]. %	[Cu]. %
Strip and Section Waste Metal	0.10	0.15	0.15
Structural Metal	0.15	0.20	0.20
Thin Tubes	0.30	0.15	0.25
Rails	0.15	0.20	0.25
Automotive Scrap	0.10	0.15	0.15

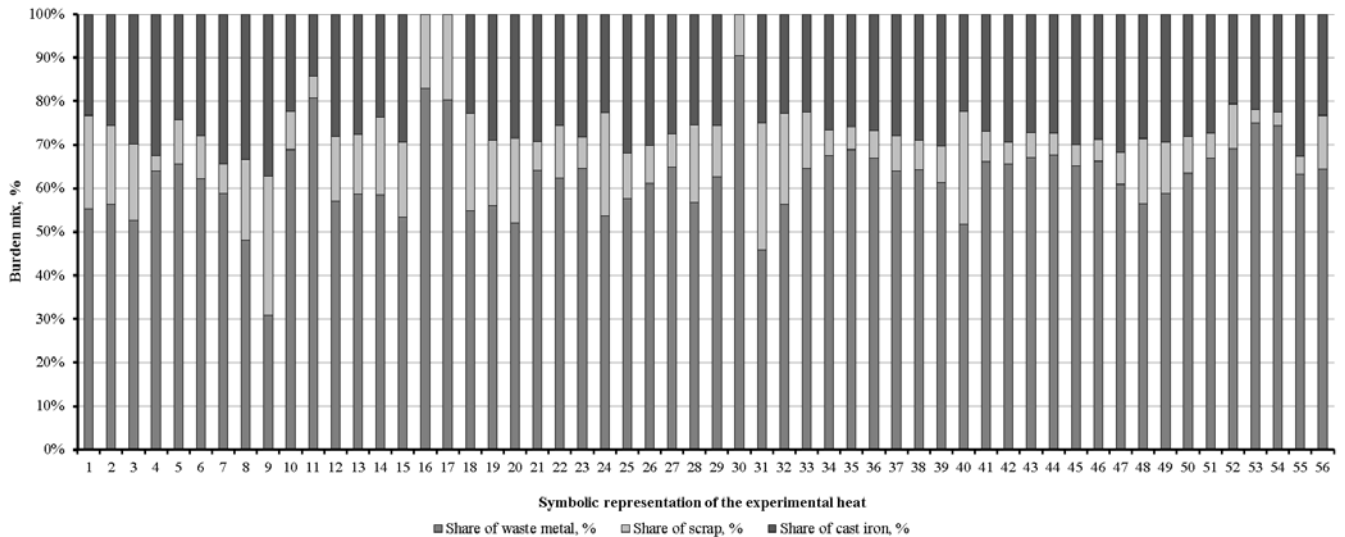


Fig. 1 Example of an unacceptable low-resolution image

TABLE II TARGET CONTENT OF CHEMICAL ELEMENTS IN STEELS INTENDED FOR DIFFERENT PURPOSES

Purpose of Steel	[Cr]. %	[Ni]. %	[Cu]. %
Russian State Standard 9045	0.02	0.04	0.04
Cord	0.05	0.05	0.05
Rod Technology Regulations 14-1-5317	0.1	0.1	0.15
Steel According to Russian State Standard 380	0.3	0.3	0.3

III. STATISTICAL ANALYSIS OF PARAMETERS OF HEATS

Taking into account that the content of these elements has a significant influence on the share of residual elements, statistical analysis of parameters of 56 heats was carried out in the electric steelmaking shop of OJSC “MMK”.

For this research the authors determined a set of data covering the structure of burden materials, heat technological parameters and steel and slag compositions. Fig. 2 shows mental representation of the building block of information chosen for the research. To evaluate the relation between the examined parameters the authors carried out the correlation analysis of frequencies and absolute values. The research results are given in Fig. 3 as graphic representation of significant relations at the level of 5%.

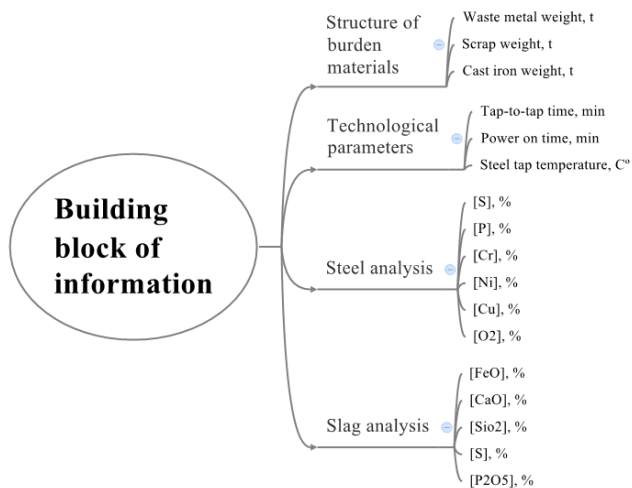


Fig. 2 Example of an unacceptable low-resolution image

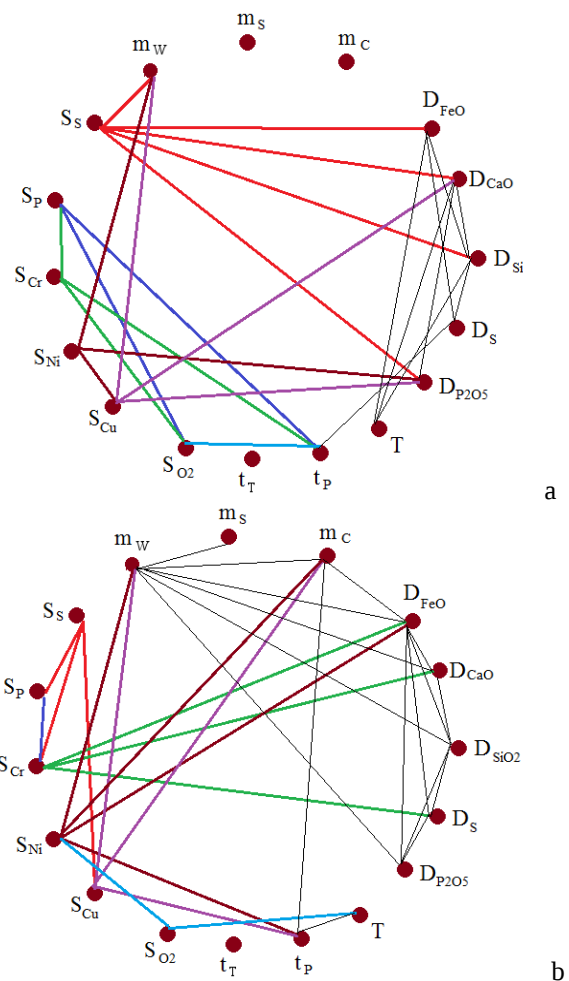


Fig. 3 Graph of significant relations: a- frequency characteristics, b- absolute characteristics

The results of the correlation analysis by the frequency characteristics and initial absolute values are given in Fig. 3. The following symbols were used in the graphic representations: m_w is the wasted metal weight, t; m_c is the cast iron weight, t; m_s is the scrap weight, t; t_T is the tap-to-tap time, min.; t_P is the power on time, min.; T is the steel tapping temperature, $^{\circ}\text{C}$; S_s , S_p , S_{Cr} , S_{Ni} , S_{Cu} , S_{O2} are the content of the following chemical elements in steel: sulphur, phosphorus, chrome, nickel and oxygen, respectively; D_{FeO} ,

D_{CaO} , D_{SiO_2} , D_S , $D_{P_{2O_5}}$ are the content of oxides and elements in slag FeO , CaO , SiO_2 , S and P_2O_5 , respectively.

Correlation analysis of frequencies was carried out to estimate the interval-probability dependence. As a result of this analysis for the examined parameters it was found that:

- there is a significant frequency interrelation between certain interval estimation of maximum frequencies for waste metal weight charged into the EAF and the content of such residual elements as sulphur, copper and nickel (Fig. 4a and 4b);

- there is a significant frequency interrelation between certain interval estimation of maximum frequencies for waste metal weight charged into the EAF and the content of such residual elements as sulphur, copper and nickel (Fig. 4a and 4b);

- frequency intervals for the content of such residual elements as phosphorus and chrome can be determined depending on the intervals for the power on time;

- there is multicollinearity for frequencies determining the composition of the slag formed;

- intervals with the highest frequency of chrome formation in the interval of 0.033–0.047% is displaced from the highest frequencies of copper formation in the interval of 0.195–0.218% and nickel formation in the interval of 0.102–0.114% along the interval scale of waste metal application three intervals leftward;

- in the range of 0.87–105.8 t for the weight of the charged waste metal with the probability of 0% we get copper content from 0.100 to 0.124% and 0.056–0.067% of nickel content with the 41% probability of getting chrome content in the interval 0.033–0.047% (Fig. 4a, 4b and 4c).

It is more traditional though to forecast processes and facts on the basis of regression equations for absolute values. On the basis of the graph analysis in Fig. 3b the authors determined the main clusters for regression examination of getting residual elements in steel.

Primary investigation of the graph given in Fig. 3b made it possible to:

- determine the main clusters for making and examination of empirical dependences (Table III);

- find a significant linear interrelation at the 5% level of residual materials content with the burden materials weight that exists for Class/Rate 4 and 5 meaning that the main source of copper and nickel in steel is the waste metal and that these elements practically do not get into steel from the scrap;

- ascertain that Classes 1–3 determine the multicollinear interrelation between the elements S_S , S_P , S_{Cr} , S_{Cu} that makes it necessary to use the system of empirically interrelated equations for their forecast;

- find out that the parameter determining the power on time has a significant linear relationship with the charged cast iron weight that adds a lot of heat and determines the thermal balance of the heat;

- Conclude that such parameter as metal outlet temperature has a significant linear relationship with the power on time parameter.

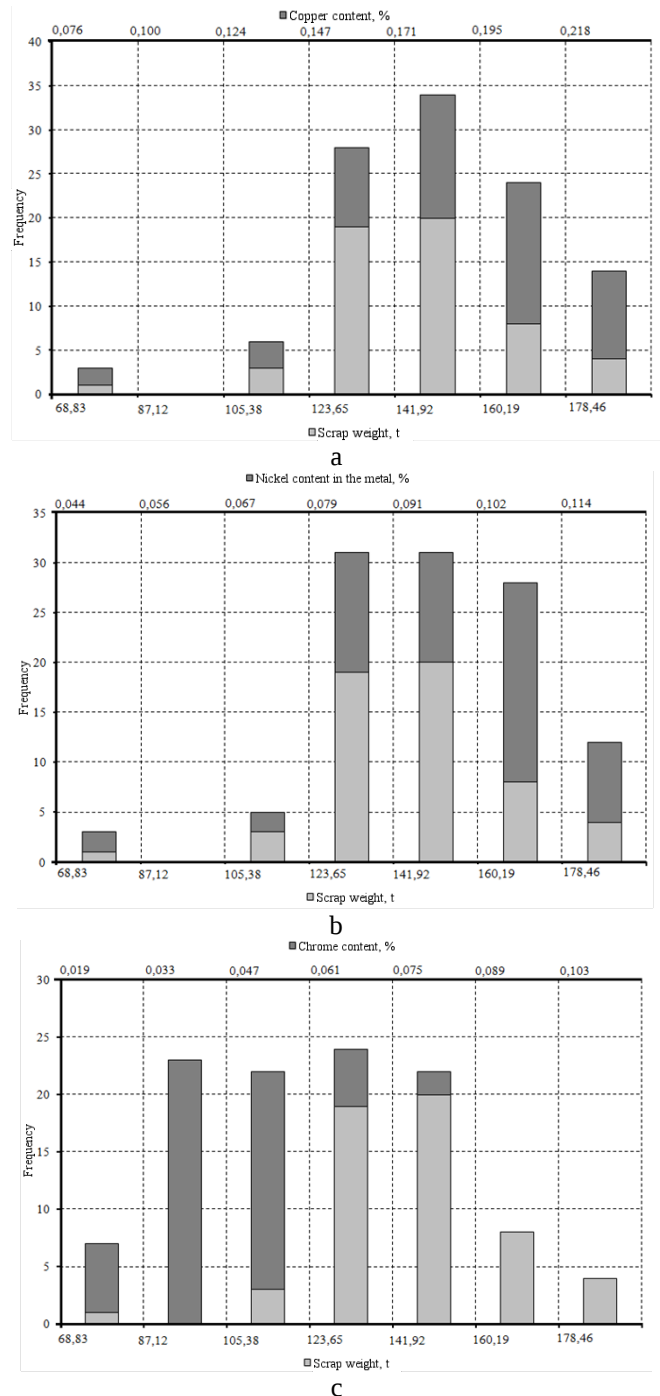


Fig. 4 Bar chart of absolute frequencies for probability estimate of obtaining residual elements in steel produced in EAF: a- copper content; b- nickel content; c- chrome content

TABLE III CLUSTERS FOR EXAMINATION OF EMPIRICAL DEPENDENCES FOR THE STUDY OF EAF PROCESSES AND PHENOMENA

Class	Residual Element	Groups of Parameters			
		Steel Analysis	Slag Analysis	Burden Structure	Technological Parameters
1	S_S	S_P , S_{Cr} , S_{Cu}	—	—	—
2	S_P	S_S , S_{Cr}	—	—	—
3	S_{Cr}	S_S , S_P , S_{Cu}	D_{FeO} , D_{CaO} , D_S , D_{SiO_2}	—	—
4	S_{Ni}	—	D_{FeO}	m_W , m_C	t_P
5	S_{Cu}	—	—	m_W , m_C	t_P
6	SO_2	S_{Ni}	—	—	T

Taking into account that the oxide content is the resultant parameter rather than the present one, in order to forecast the residual elements content in steel produced in the EAF, a system of structural equations was developed of the form

$$\begin{cases} S_{Ni} = a_{11}m_w + a_{12}m_c + \xi_1, \\ S_{Cu} = a_{21}m_w + a_{22}m_c + \xi_2, \\ S_{O_2} = b_{31}S_{Ni} + a_{33}T + \xi_3, \\ S_S = b_{42}S_{Cu} + b_{45}S_p + b_{46}S_{Cr} + \xi_4, \\ S_p = b_{55}S_S + b_{56}S_{Cr} + \xi_5, \\ S_{Cr} = b_{62}S_{Cu} + b_{64}S_S + b_{65}S_p + \xi_6, \end{cases} \quad (1)$$

where $\{S_{Ni}, S_{Cu}, S_{O_2}, S_S, S_p, S_{Cr}\}$ is a set of endogenous variables; $\{m_w, m_c, T\}$ is a set of exogenous variables; a_{ij} are empirically determined coefficients for exogenous variables; b_{ij} are empirically determined coefficients for endogenous variables; ξ_i is an empirical measure estimating the influence of unaccounted factors.

The System (1) contains two independent equations for variable S_{Ni} and S_{Cu} . For these equations the coefficients can be found on the basis of the least-squares method (LS

method). Fig. 5 shows the forecast results of residual elements content in steel for S_{Ni} and S_{Cu} . The following symbols were introduced for lines in Fig. 5: 1—the recommended value for Russian State Standard 9045; 2—cord; 3—rod Technology Regulations 14-1-5317; 4—Russian State Standard 380 (Table II).

If we denote the number of endogenous variables in the j -th equation of the system as H and the number of exogenous variables that are contained in the system but do not appear in this equation as D , then the model identifiability can be expressed in the form of a countable rule:

- $D + 1 = H$ - the equation is identifiable;
- $D + 1 < H$ - the equation is unidentifiable;
- $D + 1 > H$ - the equation is superidentifiable.

According to the necessary criterion of identifiability of the system of equations we can conclude that the System (1) is superidentifiable [4]. Taking into account intercorrelability and multicollinearity of initial data its parameters can be determined on the basis of the two-sweep least-squares method to forecast the residual elements content in steel.

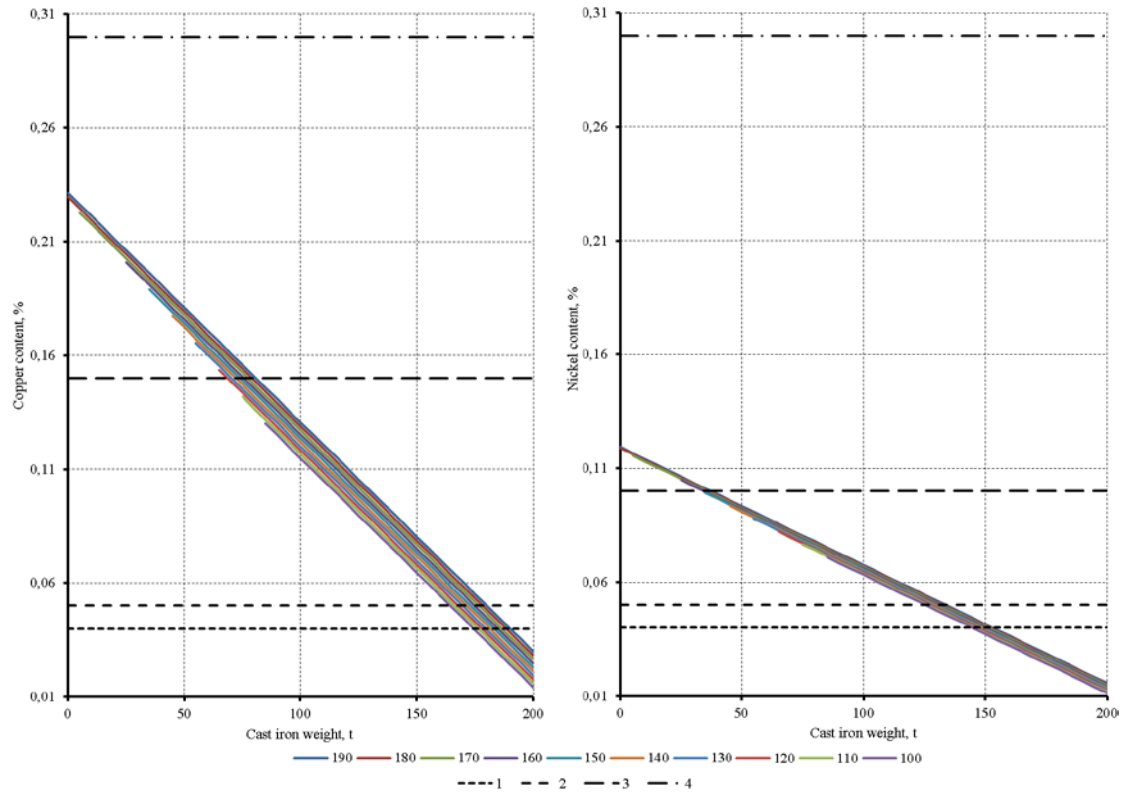


Fig. 5 Nomographic chart of residual elements content forecast in steel, particularly nickel and copper content, at different waste metal weight

As a result of the two-sweep least-squares method application we can develop a system of equations:

$$\begin{cases} S_{Ni} = 0,000048m_w - 0,000519m_c + 0,1102, \\ S_{Cu} = 0,000175m_w - 0,001m_c + 0,19807, \\ S_{O_2} = 0,7365S_{Ni} + 0,001443T - 2,3108, \\ S_S = 0,1174S_{Cu} + 1,4977S_p + 0,197S_{Cr} + 0,00154, \\ S_p = 0,1717S_S + 0,0859S_{Cr} - 0,00302, \\ S_{Cr} = -0,07994S_{Cu} + 0,9592S_S + 1,6385S_p + 0,0018. \end{cases} \quad (2)$$

The equations are reliable by Fisher's ratio test and the coefficients are significant by Student criterion at 5% level.

The forecasts obtained in accordance with the System (2) specify the burden materials ratio contributing to the target residual elements content. The recommended ranges of the burden materials ratio for the total charge weight up to 210 t are given in Fig. 6a for obtaining target copper content and in Fig. 6b for obtaining target nickel content. Points A and B (Fig. 6) are equilibrium points for waste metal and cast iron, so additional research work should be done to calculate power costs in the tap-to-tap cycle.

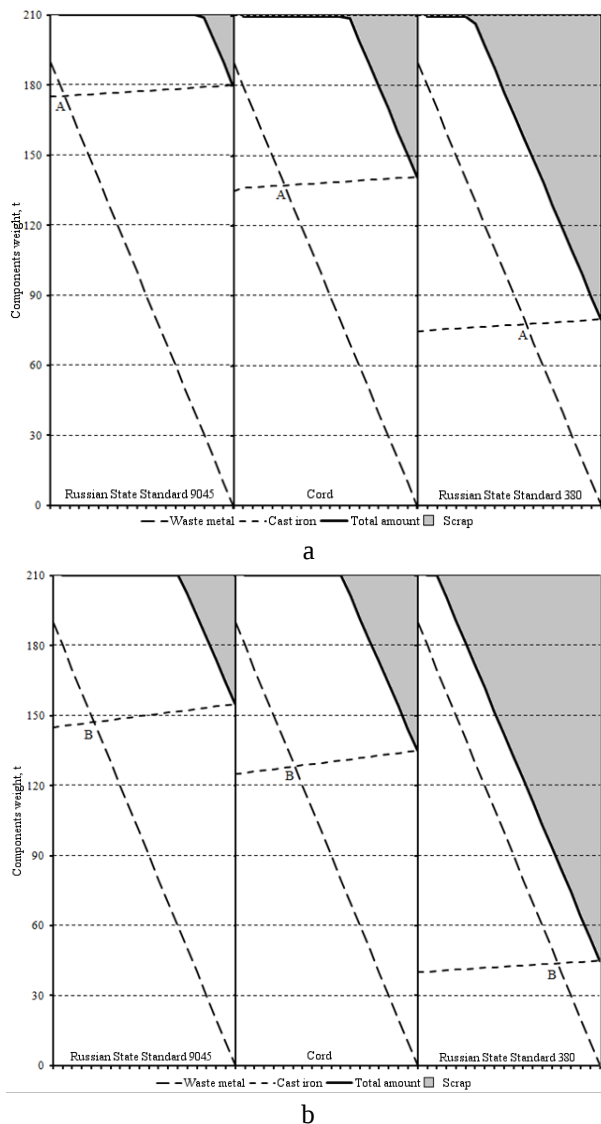


Fig. 6 Ranges of ratios of burden materials charge for obtaining target residual elements content: a- copper; b- nickel

IV. CONCLUSIONS

The target value of such residual elements as copper and nickel in the steelmaking process according to the State Standard 380 can be obtained at any ratio of burden materials. Acceptable modes make it possible to obtain the target residual elements content (copper and nickel) and to select the economy mode concerning the energy costs. Application of the developed empirical system of interrelated equations makes it possible to make more flexible ratios of burden materials thus resulting in the choice of the best mode of the process control and ensures the minimum energy costs.

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She have published 146 works, owned 17 patents and intellectual property certificates, and published 72 teaching and methodical aids. The most prominent works include:

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- 2) Continuously-cast billet thermal state multicriteria optimization (Penza, Russia: High education institutions news. Volga region, 2009).
- 3) Steel Continues-casting process automated control system ergonomic modules (Novosibirsk, Russia: Information technologies: drifts, 2011).

Dr. Logunova is currently member of Engineering Sciences Academy named after Prokhorov. Dr. Logunova's innovational works were rewarded gold medal at the 4th Moscow International innovations and Investments Show (Moscow, 2004), bronze medal of the 8th Moscow International innovations and Investments Show (Moscow, 2008), and "Designing of Processing and quality assessment of continuously-cast billet on continues-casting machines software" scientific project received Diploma for 2nd place in "IT and electronics" section of the second regional innovations and investments show (Chelyabinsk, 2006). Dr. Logunova's inventive activity's results were highlighted in "South Ural Inventor" competition by Chelyabinsk Region government, where Dr. Logunova won the first prize in "Information and telecommunications technologies section". Dr. Logunova was rewarded by Chelyabinsk region's Governor a honored diploma in 2011 for her active scientific work.



Vladimir V. Pavlov was born in Magnitogorsk, Russian Federation on April 3, 1958. He finished metallurgical faculty in Magnitogorsk State Technical University, Magnitogorsk, Russia in 1984. From 1984 he worked at Magnitogorsk Iron and Steel Works in the following positions: apprentice steelworker open-hearth shop # 2, engineer, senior engineer, and head of department of the central laboratory enterprise. Since 1996 he has worked as a leading engineer technologist. His total number of scientific publications is 37, patents are 56, and educational works are 3. The most prominent works include:

- 1) Information system for continuously-cast steel billet quality control basics (Tver, Russia: Software products and systems, 2008).
- 2) Production of steel cord at Magnitogorsk Iron and Steel Works (Moscow, Russia: Metallurgist, 2007).
- 3) Methods of choosing modes of secondary cooling of continuous-cast billet in multicriteria environment (Moscow, Russia: Metallurgical heat engineering: history, current status: 3rd international scientific and practical conferences digest).

Mr. Pavlov's innovational works were rewarded gold medal at 4-th Moscow International innovations and Investments Show (Moscow, 2004), the Grand Prize at the Moscow International Salon of inventions and innovative technologies "Archimedes-2006" and two gold medals at the Moscow International Salon of inventions and innovative technologies "Archimedes-2007" (Moscow). Mr. Pavlov is awarded named after G.I. Nosov.



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1) Steel Continues-casting process automated control system ergatic modules (Novosibirsk, Russia: Information technologies: drifts, 2011).

2) Complex steel production management subsystem using small fraction scrap metal (Moscow, Russia: Theoretical and Practical Issues of Management, 2011).

3) Stage of perfection technology of steel melt in arc furnace at use of a metal breakage of small fraction (Moscow, Russia: Electrical Metallurgy, 2011).

Mr. Matsko won the prizes of the regional competition of research works of students and young scientists of higher educational institutions located in the Chelyabinsk region and of the competition grants of research works of students, graduate students and young scientists of Federal State Budgetary Educational Institution of Higher Professional Education “Magnitogorsk state technical university named after G.I. Nosov” in 2011. He was awarded the scholarship of President of the Russian Federation in 2012.



Ivan V. Pavlov was born in Magnitogorsk, Russian Federation on January 25, 1988. He acquired specialist degree in metallurgy of ferrous metals in Magnitogorsk State Technical University, Magnitogorsk, Russia in 2010. He became a postgraduate student to specialty “Mathematical simulation, numerical methods and software complexes” in Magnitogorsk State Technical University, Magnitogorsk, in 2010.

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He has published one work: Interaction model of large-sized scrap of graphite electrodes in an electric arc furnace (Orenburg, Russia: Computer integrated manufacturing technology and information support, 2011).